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Use of ^{10}Be exposure ages and Schmidt hammer data for correlation of moraines in the Krkonoše Mountains, Poland/Czech Republic

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with 8 figures and 2 tables

Summary. Exposure ages and relative-age data are presented from eight sites in the Łomnica and Łomniczka valleys to provide essential information for reconstructing local glaciation chronology. A combination of ^{10}Be exposure ages and Schmidt hammer data obtained for moraines indicate relatively short period of glacier accumulation lasting from 17.0 ± 0.4 ka to 13.6 ± 0.9 ka. Exposure age of 8.4 ± 0.3 ka measured on the lowermost section of the Łomnica cirque headwall further confirms the view of glacier preservation in favourable sites until the beginning of the Holocene. A comparison of the obtained chronological data with timing of mountain glaciation in the nearby Úpa Valley is used to propose the first correlative model of Late Quaternary glaciation in the eastern part of the Krkonoše Mountains. The correlation implies that the lowermost preserved moraines originated during the local maximum of the last glaciation whereas recessional moraines were deposited until the Lateglacial period. A subsequent melting of glaciers terminated at the beginning of the Holocene. The implications of the model are discussed and further investigations are suggested to extend its validity to the whole mountain area.

Key words: moraines, ^{10}Be exposure dating, quartz grain microtextures, deglaciation chronology

1 *Introduction*

Evidence of Quaternary mountain glaciation in the Krkonoše Mountains has been recognized at the end of 19th century (Partsch 1894). Since that time there have been a number of geomorphological investigations, identifying glacial landforms and extent of local glaciers (see Migoń & Pilous 2007). By contrast, the timing of the Quaternary glaciations remained unknown until recently and proxy for the glaciation chronology appeared sporadically. Attempts to solve the question of chronology of the local glaciation were usually based on morphological evaluation of the glacial landforms, which was not sufficient enough. Glacial landforms were attributed to Middle and Late Pleistocene but without any direct evidence (Sekyra 1964). Some progress has been reached lately when the relative age of moraines was suggested based on surface weathering of morainic boulders. Depending on the age the morainic material varies in the intact rock strength, the presence of characteristic surface microforms and weathering rinds (Traczyk 1989).

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The first geochronological data for the glacial relief were gathered at the turn of 20th century providing rough estimations of the Late Quaternary glacial episodes in the northern part of the Krkonoše Mts. A single radiocarbon age (9,970 ± 180 ka BP) of organic sediment from the bottom of the Łomnica valley was interpreted as the beginning of the postglacial lake development whereas TL data (87–93 ka) from the western Krkonoše Mts gave the first indication of pre-Late Weichselian glaciation (Chmal & Traczyk 1999). Exposure-age dating of glacial surfaces in the Labe and Úpa valleys has brought information on deglaciation chronology more recently (Mercier et al. 2000). The recession of the Late Quaternary glaciation started before 15 ka BP and glaciers persisted in suitably orientated parts of cirques until the beginning of the Holocene (Braucher et al. 2006). However, all the dated glacial landforms are situated within troughs implying earlier glaciation of the valleys (Engel 2003). According to current view local glaciers were probably formed already during the pre-Weichselian but their development was only confirmed in the Late Quaternary (Carr et al. 2007).

The diverse time span of applied dating techniques and isolated pattern of investigated area discouraged the correlation of the Quaternary glaciations in the Krkonoše Mts. The moraines were reported as Würmian, Rissian and earlier in the northern part of the mountains (Chmal & Traczyk 1999). A different interpretation implying the Late Quaternary origin of all preserved moraines results from the recent investigation in the southern part of the mountains (Engel 2003, Carr et al. 2007). The contrasting hypotheses represent a problem for the establishment of the uniform stratigraphy and timing of Quaternary glaciation in the region. Consequently it is not possible to include the local glaciation of the Krkonoše Mts into the chronostratigraphic frame of the Quaternary glaciations of other parts of Central Europe (see Ehlers & Gibbard 2004). Therefore, it is currently difficult to utilize the local knowledge for solving problems of environmental changes in the Late Quaternary (Gillepspie & Molnar 1995).

In this paper, we use in situ produced cosmogenic dating and relative-age dating to determine glaciation chronology in the Łomnica and Łomniczka valleys. The study area was selected because of abundance of well-preserved and morphologically distinct moraines and their clear relative age sequences. The same methods as in the nearby Úpa valley have been adopted (Mercier et al. 2000, Carr et al. 2007) so that comparable results will be obtained. The correlation of the local chronologies based on obtained and previously reported data is tentatively suggested.

2 *Study area*

The area under investigation is located in the Sudetes Mountains in Central Europe. It is delimited to the eastern part of the Krkonoše Mts, extending north-westwards from Sněžka Mountain (1,602 m, fig. 1). The mean annual temperature in the study area decreases with altitude from about 5.7 to 1.5 °C. The temperature range is estimated from data collected from 1991 to 2010 at Karpacz (575 m), Luční (1,410 m) and Sněžka weather stations, located up to 3 km from the study area. The mean annual precipitation ranges between 1,042 and 1,102 mm/yr (Głowicki 2005). The Krkonoše Mts consist mainly of granites and metamorphic rocks (mica schist, phyllites and gneiss). A main ridge of the mountains is built by fine grained equigranular granite whereas flanks are made up of coarse- to medium-grained porphyritic granite (Chaloupský 1965). A narrow zone of contact metamorphism (mica schist and metamorphic hornfels) marks the southern boundary of the granite area and metamorphic unit.

The relief pattern of the eastern Krkonoše Mts reflects bedrock properties comprising a large plateau limited by WNW-SES oriented ridges. The summit plateau

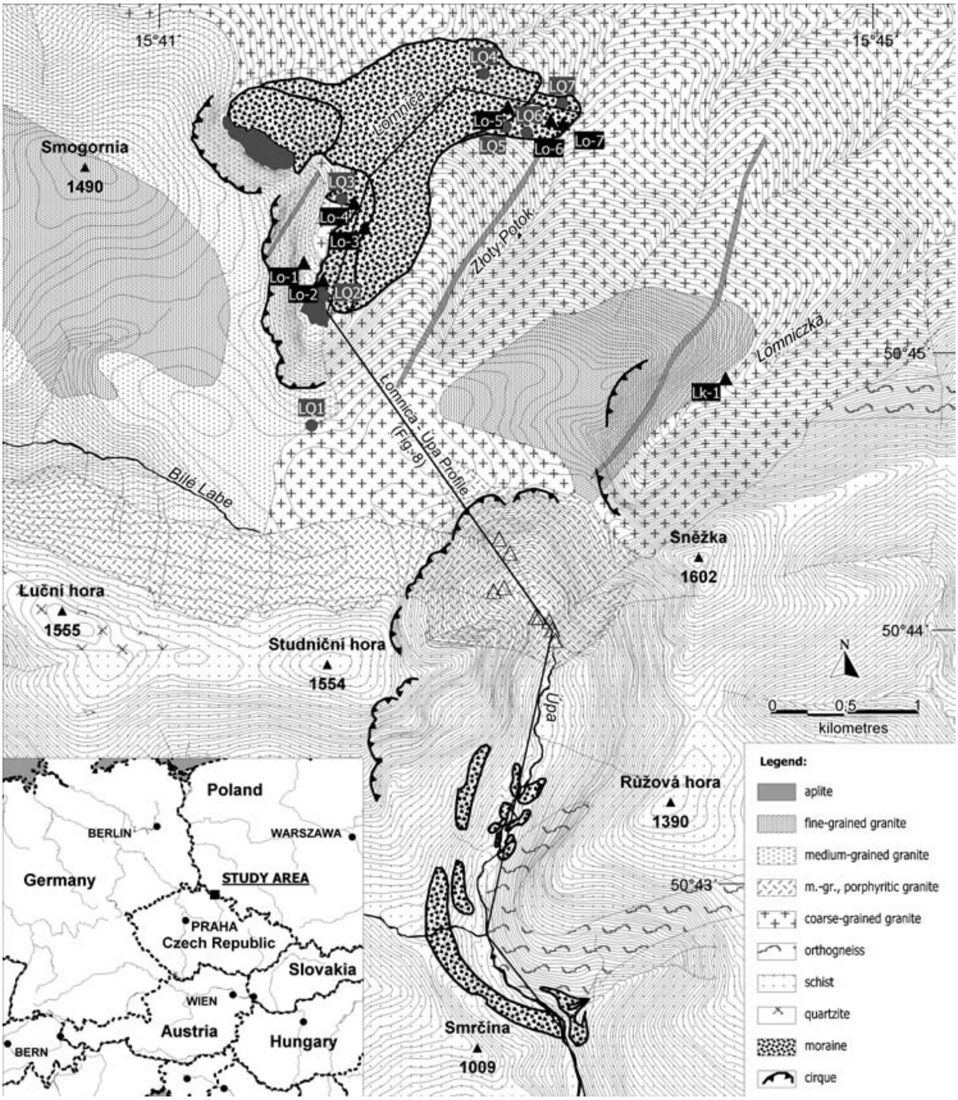

Fig. 1. Simplified geomorphological and geological map of the study area in the eastern part of the Krkonoše Mountains with location of sampling sites (grey circles – sites sampled for quartz grain analyses, solid triangles – ^{10}Be dating sites, unfilled triangles – ^{10}Be data reported by Braucher et al. 2006).

(1,400–1,450 m a. s. l.) has originated during the Paleogene or Neogene (Jahn 1980, Migoń 1997). The Bílé Labe and Łomniczka valleys are incised into the summit surface following the less resistant zones of discontinuities (Dumanowski 1963). The northern and southern flanks of the ridges are dissected by deeply incised valleys of the Łomnica and Úpa Rivers. Quaternary valley glaciers developed transformed valley heads to well-developed cirques. All the cirques are asymmetric having the steepest headwalls cut into the E and NE margin of the summit plateau (fig. 2). A lee-ward position of the cirques and their morphology was attributed to preglacial relief pattern and prevailing west winds (Partsch 1894, Migoń 1999).

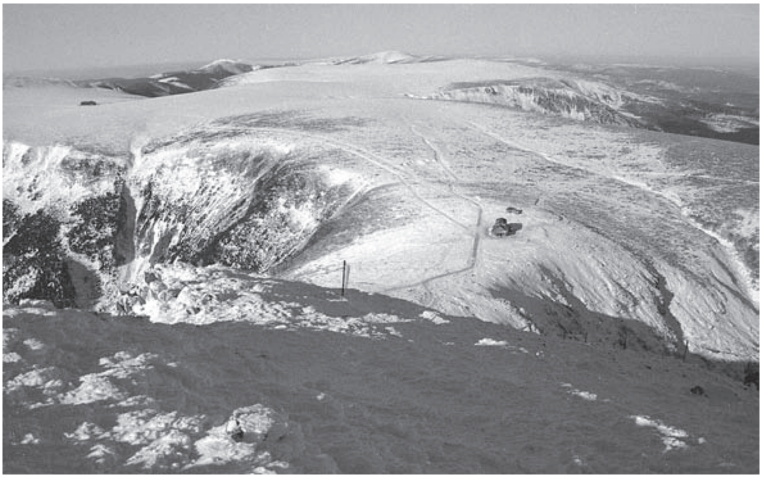

Fig. 2. The summit plateau with cirque edges of the Úpa (left), Łomnica (right) and Łomniczka (right bottom) valleys seen from the east.

Fig. 3. Dated ridge of the end moraine (II) in the Łomnica Valley.

Cirques incised into the plateau margins built by metamorphic rocks are larger than cirques which border the NE granite part of the summit surface. The first group is represented by Úpa and Łomniczka Cirques which are characterized by long upper edges (2,800 m and 1,500 m, respectively) and big depths (500 m and 300 m, respectively). Headwalls are steeper and higher (up to 200 m) in the Úpa Cirque whereas rock steps in Łomniczka Cirque are lower than 50 m. Minor cirques are cut into the summit plateau along its border with the Łomnica valley. The headwall of the Mały Staw cirque is 2,200 m long and 150–190 m high. The Wielki Staw cirque is delimited by 1,350 m long upper edge and 170–190 m high rock walls. Moraine-dammed lakes are located on the bottom of the cirques in the Łomnica valley.

The well-developed series of moraines have been identified in the Łomnica valley (fig. 3). Lateral and terminal moraines are preserved from the cirques downvalley to 900 m a. s. l. The height of terminal moraines ranges from 30–40 m in the cirques to 15–25 m in the valley. Within the Łomniczka and Úpa valleys, only relics of lateral moraines have persisted. In deeply incised valleys with narrow bottoms (100–150 m), terminal moraines were destroyed by fluvial processes and mass movements after glacier recession. Among other landforms resulting from moraine destruction a large fan was deposited at the mouth of the Łomniczka valley near Karpacz (Büdel 1936).

3 *Methods*

3.1 *Site selection for surface exposure dating*

To determine the ^{10}Be exposure age of the local glaciation, stable boulder on the surface of moraines have been identified and sampled together with the bedrock at the foot of a cirque headwall (Site Lo-1; fig. 1). All sampled sites were composed of coarse-grained biotite porphyritic monzogranites, except for Lo-1 and Lo-2, which was composed of medium-grained biotite monzogranites. Samples were collected from the surface of 1 to 2.5 m high boulders that lie at the top of moraine ridges or on flat surfaces, far from steep slopes. Boulders on four terminal moraines were sampled in the upper Łomnica Valley (Sites Lo-2 to Lo-7) and one sample was taken from a relic of a moraine ridge in the Łomniczka Valley (Site Lk-1). Although the ridge has lateral location it represents the only preserved moraine in the valley which can constrain the timing of local glaciation. Samples were collected from rock surfaces (upper 3 cm) using chisel and hammer. The dip and aspect of sampled surfaces were measured with clinometers and compass. Geographic positions and altitudes of each site were recorded with GPS. Table 1 contains site characteristics and description.

3.2 *Sample preparation and data treatment*

Samples were crushed and sieved. The 0.25 to 1 mm quartz fraction was decontaminated by successive acid leaching ($HCl + H_2SiF_6$ then dilute HF). Purified quartz was spiked with 100 µl of a 3,025 ppm home-made carrier then dissolved in 48 % HF. Beryllium was complexed by acetyl acetone in a 50 % EDTA solution then extracted using solvent extraction. Beryllium hydroxides were dried and oxidized at 800 °C to BeO. Beryllium oxide was mixed to 325 mesh niobium powder, prior its measure-

Table 1. Sampling sites for ^{10}Be surface exposure dating.

Sample	Altitude (m)	Boulder height (m)	Sample surface dip/aspect (°)	R-value intact/prepared	Site description and moraine zone
Lo-1	1,195	–	27/325	53.2/72.1	bedrock outcrop, foot of cirque headwall
Lo-2	1,185	1.9	0/0	34.3/71.2	crest of inner moraine ridge (III)
Lo-3	1,175	1.0	7/120	40.2/69.2	crest of lateral moraine (II)
Lo-4	1,140	0.6	10/80	42.4/65.5	crest of end moraine (III)
Lo-5	985	1.2	0/0	39.8/65.4	crest of end moraine (II)
Lo-6	925	2.5	0/0	35.5/64.6	surface of terminal moraine (I)
Lo-7	910	1.2	0/0	37.2/60.1	surface of terminal moraine (I)
Lk-1	1,055	1.0	3/90	35.9/66.4	crest of lateral moraine, 20 m from talus foot

ment at ASTER, the French AMS located at CEREGE, Aix en Provence. $^{10}Be/^{9}Be$ ratios were calibrated directly against the National Institute of Standards and Technology standard reference material no 4,325 by using an assigned value of $(2.79 \pm 0.03) \times 10^{-11}$. A ^{10}Be half life of $(1.387 \pm 0.012) \times 10^{6}$ years was used based on recent papers of Korschinek et al. (2009) and Chmeleff et al. (2009).

In order to determine Cosmic Rays Exposures (CRE) ages from the ^{10}Be concentrations measured in the quartz fractions, a modern ^{10}Be spallation production rate at sea level and high-latitude of 4.5 ± 0.3 atoms g/yr Stone (2000) was used. This sea-level and high-latitude production rate has then been scaled for the sampling altitudes and latitudes using the scaling factors proposed by Stone (2000). An additional muon production of 2.1 % of the total production (~ 0.097 at/g/yr at SL) and scaled to the sampling area for altitude using an attenuation length of 240 g/cm^2. Surface production rates were also corrected for local slope and topographic shielding due to surrounding morphologies following Dunne et al. (1999). The shielding from snow was estimated according to Reuther (2007) using average snow density of 0.3 g/cm^3 and values for the mean thickness and the duration of snow cover measured by Głowicki (1977), Kwiattkowski & Lucerski (1979) in the study area. Analytical uncertainties (reported as 1 sigma) include a conservative 0.5 % uncertainty based on long-term measurements of standards, a 1 sigma statistical error on counted ^{10}Be events, and the uncertainty associated with the chemical and analytical blank correction (associated $^{10}Be/^{9}Be$ blank ratio was $1.7 \pm 0.5 \times 10^{-15}$). CRE ages were calculated using the physical parameters determined by Braucher et al. (2003) (attenuation lengths of 150, 1,500 and 5,300 g/cm^3 for neutrons, slow and fast muons respectively. Analysis of variance (ANOVA) was used to determine whether there exist any chronological differences among groups of dated moraines. The statistical significance of a relationship was tested by F test with p-level 0.05.

3.3 *Schmidt hammer measurements*

Schmidt hammer (SH) records were undertaken at each ^{10}Be sampling site in accordance with the operating guidelines recommended by Day & Goudie (1977). The standard N-type of SH was applied to the same part of the dated rock surface not far then 50 cm from sampling points. 25 hammer impacts were taken on the naturally weathered surface first (Matthews & Shakesby 1984). The surfaces were then polished using an electric grinder and re-examined with a hammer (Katz et al. 2007). Both datasets were processed following one of the three most accepted methods among the different SH rebound techniques (e. g. Hubbard & Glasser 2005). First, the mean and the standard deviation of the recorded readings were calculated. Then, the five values with the greatest deviation for each surface were excluded from the dataset and new mean rebound (R) values were calculated from the remaining 20 values. The resulting mean R-values were taken as representative for each surface.

The mean R-values represent degree of surface weathering which can be used as a proxy for relative age of sampled surfaces. The mean R-values for the dated surfaces were compared with published SH records obtained on five preserved moraines in the Obří důl (Carr et al. 2007). A comparison of measured and published R-values provides the data that allow limited correlation of moraines in the Łomnica and upper Úpa valleys. The mean R-values for the prepared surfaces allow more discriminating correlations with granite outcrop surfaces in the Sudetes Mountains (Černá & Engel 2010).

3.4 *Quartz grain microtextures*

The morphology of quartz grains was studied in order to determine the mode of transport and to reveal possible post-depositional changes. The history of glacial accumulations is important for correct interpretation of obtained exposure ages which are often biased by overprinting or spalling of moraine surfaces (e.g. Cerling & Craig 1994, Putkonen & Swansson 2003). An analysis of quartz grain microtextures may reveal various post-depositional processes and is thus useful for elimination of errors in exposure datasets.

Altogether seven samples of coarse-grained sand representing investigated bedrock and moraine belts in the Łomnica valley were analyzed. The granite bedrock sample (LQ1) was collected from the slightly inclined (4°) surface of the plateau between Łomnica and Łomniczka cirques. This sample represents weathering mantle which has developed during the Quaternary as a result of periglacial weathering and solifluction movements. Microscope analysis of quartz grains obtained from this sample allow to recognize typical microstructures formed due to the physical and chemical weathering processes and distinguish this microstructures from those resulted as an effect of grain abrasion and surface destructions in glacial environment (LQ2–LQ7). For the microtexture analysis 20–25 typical grains of 0.5–1.0 mm size were selected from each sample using the light microscope. The grains were rinsed in 10% HCl and washed using distilled water. Finally, individual grains were gold coated. Micromorphology of the grains was analyzed using the scanning electron microscope (SEM). The atlas of grain surface morphology of Mahaney (2002) and description of quartz grain microtextures of Helland & Holmes (1997) was used for microtexture evaluation.

4 *Results*

4.1 *Chronology of moraines*

Geomorphological position and morphology of glacial deposits indicate that three groups of moraines can be distinguished in the Łomnica valley (Fig. 4, zones I to III). The zone I consists of relics of lateral and terminal moraines at the confluence of the Łomnica and Złoty Potok Rivers. These moraines were incised by Łomnica after the deposition. Pronounced ridges of the second (II) moraine zone adjoin the deposits of the zone I. Well-developed melt-out depressions on lee side of the moraines are characteristic feature of the zone II. Lateral moraines representing this zone can be traced up to the cirques of Wielki and Mały Staw Lakes. The highermost located zone III consists of the best-preserved moraines in the cirques. Terminal moraines of this zone are 30–60 m high which indicates rapid transport of material from headwalls into the cirques. Varying morphology and preservation of moraines within described zones suggest that three main phases of glaciation occurred in the Łomnica valley. Moraines of the zones I and II were deposited by valley glacier whereas the youngest zone (III) represents cirque type of glaciation.

Two moraines from each zone were dated in the Łomnica valley. The lowermost preserved terminal moraine is located 3.4 km down valley from the north headwall of the cirque above the Mały Staw Lake. Two boulders from this moraine (Sites Lo-6 and Lo-7) yield a similar age conveyed by a mean value of 15,923 ± 777 yr^{-1} (fig. 4). A well-preserved and more voluminous end moraine located 350 m up valley (Lo-5) yield an age of 16,531 ± 617 yr^{-1}. The similar age (16,994 ± 446 yr^{-1}) was calculated for the sampled boulder (Lo-3) from the relevant lateral moraine higher in the valley. Two boulders from small moraine ridges closing the cirque (Lo-4) and the Mały Staw Lake (Lo-2) show an exposure age of 14,765 ± 523 and 13,631 ± 879 yr^{-1} respectively. The surface of the cirque headwall at its transition to the cirque bottom yields the youngest age of 8,361 ± 332 yr^{-1}. In the Łomniczka valley, we have obtained the only

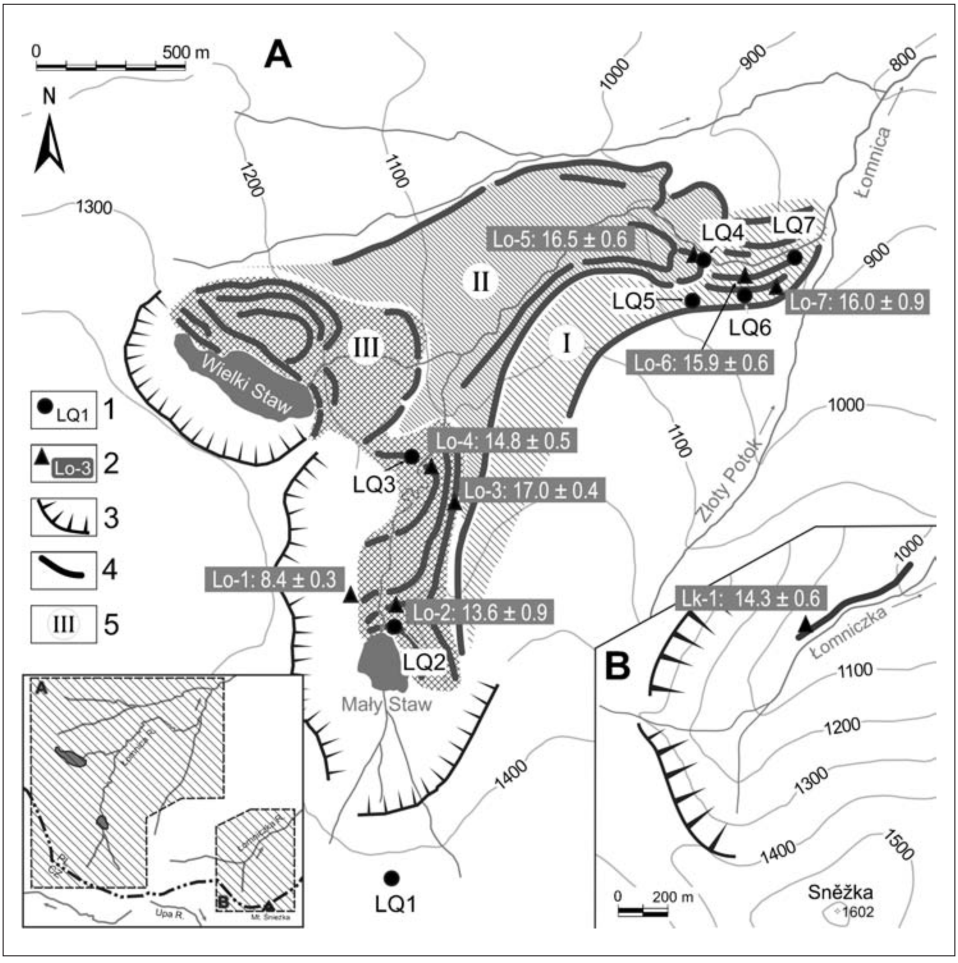

Fig. 4. Łomnica and Łomniczka Valleys with the locations of moraines and summary data of ^{10}Be dating. 1 – quartz grain samples sites; 2 – dated surfaces with ^{10}Be ages; 3 – cirques; 4 – moraine ridges; 5 – moraine zones.

Table 2. Cosmogenic ^{10}Be exposure ages.

Sample	Sample mass (g)	Production rate ($at^{-1} g^{-1} yr^{-1}$)	Mean snow cover depth/duration (cm/month)	Shielding correction	^{10}Be concentration ($at^{-1} g^{-1}$)	^{10}Be uncertainty ($at^{-1} g^{-1}$)	^{10}Be Age (yr)
Lo-1	22.174	12.61	164/6	0.8416	93,482	3,709	8,361 ± 332
Lo-2	30.421	12.86	164/6	0.8642	155,164	10,006	13,631 ± 879
Lo-3	22.505	12.78	162/5	0.8900	197129	5,168	16,994 ± 446
Lo-4	24.660	12.44	143/5	0.9011	168,956	5,981	14,765 ± 523
Lo-5	24.857	10.96	127/5	0.9108	168,119	6,278	16,531 ± 617
Lo-6	28.546	10.44	125/5	0.9120	153,936	6,038	15,870 ± 622
Lo-7	29.028	10.32	124/5	0.9126	153,259	8,935	15,975 ± 931
Lk-1	23.219	11.56	130/5	0.9062	153,276	6,183	14,294 ± 577

age for a lateral moraine deposited by a short valley glacier. The moraine elongated at the foot of the SE facing slope (Site Lk-1, fig. 4) lies between 1.1 and 1.6 km downvalley from the NE oriented cirque headwall. ^{10}Be age of 14,294 ± 577 yr^{-1} on a sampled boulder from the lateral moraine constrains the Late Weichselian timing in the study area. All mentioned ^{10}Be ages are reported in table 2.

The ANOVA test shows that there is a significant difference in age among the three moraine zones in the Łomnica valley. The F-score implies that the biggest difference is between the second (II) and the third (III) groups of moraines ($F(1;10) = 35.8594$, $p = 0.0001$) whereas the smallest difference in chronological classification exists between the first (I) and the second groups of moraines ($F(1;10) = 5.2859$, $p = 0.0443$). The apparently young age of the lowermost moraines (I) can be explained by post-depositional tilting or rolling. To validate this interpretation the weathering of boulder surfaces was measured with SH and grain size microtextures of nearby sediments was analyzed.

4.2 *Schmidt hammer R-values*

R-values measured on investigated granite surfaces range between 34.3 and 53.2 (table 1). The highest value was recorded on a glacially smoothed surface of granite bedrock at the foot of the cirque headwall (Site Lo-1). The sampled surface at this site represents the youngest section of the glacial landscape in the study area. The uppermost end moraine damming the Mały Staw Lake shows a mean R-value of 34.3 which is apparently lower than any other in the recorded dataset. This anomaly may be explained by different granite texture of tested surface (medium granite) which is more prone to weathering than homogeneous and more evenly jointed fine-grained granite boulders at remaining sites. R-values of sampled surfaces on other moraine belts decrease downvalley ranging from 42.4 at the nearest end moraine (Lo-4) to a mean value of 36.6 for two boulders on the lowermost terminal moraine (Lo-6 and Lo-7). The sampled surface on the lateral moraine in the Łomniczka valley shows a comparably low mean R-value (35.9) as the terminal moraine in the Łomnica valley.

4.3 *Quartz grain microtextures*

Quartz grains from the gruss sample (LQ1) have medium to high relief. All grains are frosted and very poorly rounded with frequent solution pits, crevasses and oriented each pits on the surface (fig. 5). The dissolution surface indicates the action of intensive chemical weathering in the formation of the surface relief (fig. 6A). Up to 10 μm long conchoidal fractures and fracture faces are the most common mechanical features (fig. 6B). Amorphous precipitation occurs on the surface of most of the grains whereas abraded grains comprise up to 45 % of the sample.

The samples which represent glacial deposits show the effects of intensive mechanical processes and chemical weathering. They are characterized by a high frequency of abrasion microtextures ranging from 61 % (LQ5) to 100 % (LQ7). The grain surfaces are dominated by conchoidal fractures, linear steps and subparallel linear fractures (fig. 6C and 6D) which is indicative for glacial environment (e. g. Mahaney 2002, Rose & Hart 2008). Other frequent mechanical features are small conchoidal fractures (< 10 μm), arc-shaped steps, straight and curved grooves or deep

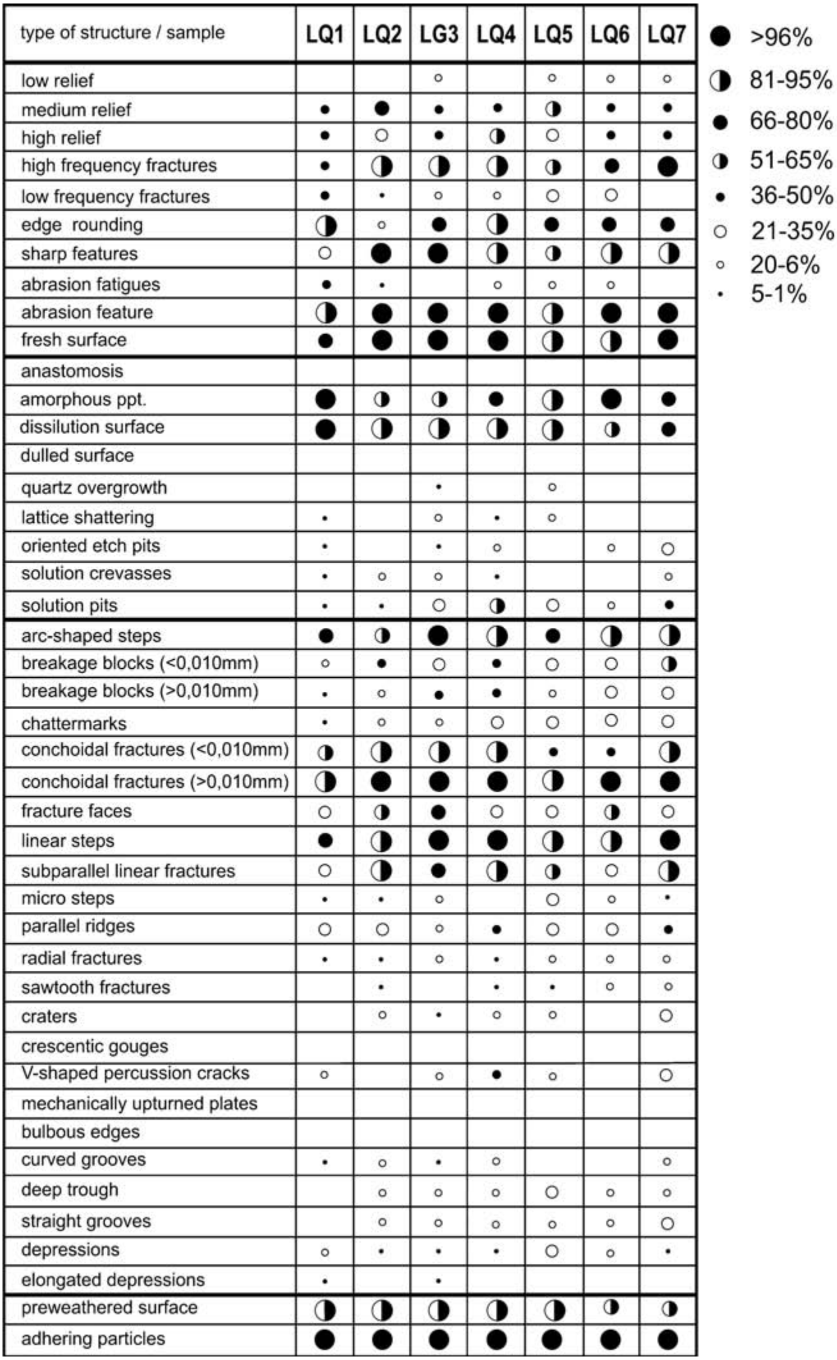

Fig. 5. Summary graph of microstructures on the quartz grain surfaces from the in situ waste deposits (LQ1) and glacial deposits from the Łomnica Valley (LQ2 to LQ7).

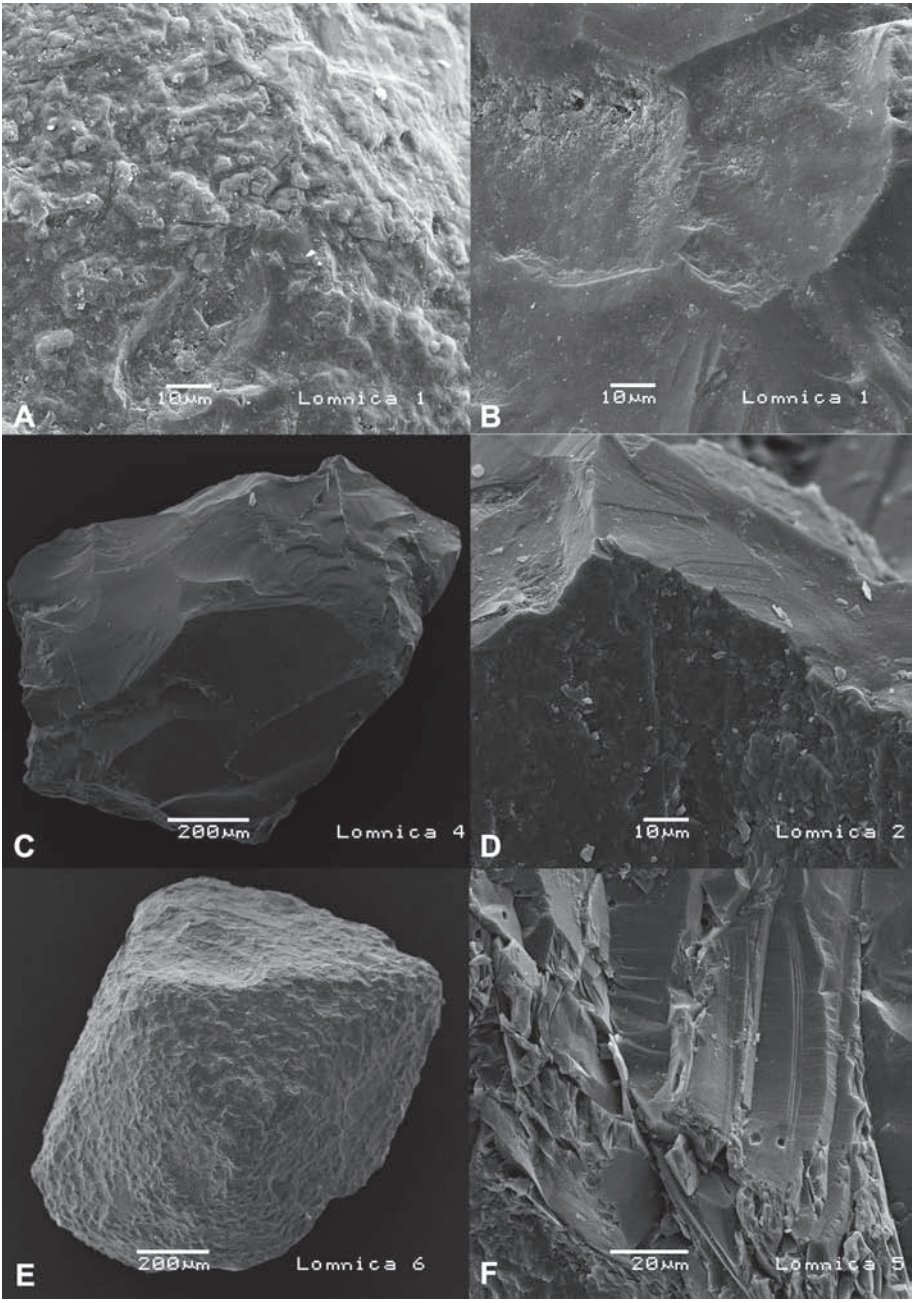

Fig. 6. Quartz grains from LQ1 site and from glacial deposits. A – the fragment of quartz grain with dissolution surface; B – quartz grain with fresh conchoidal fractures on chemical weathered surface; C – quartz grain with fresh conchoidal fractures (> 10 µm); D – sharpen corners as an effect of crushing processes; E – general view of quartz grain with dissolution surface; F – the breakage blocks microstructure as an effect of frost weathering.

troughs. Traces of dissolution surface and amorphous precipitation due to chemical weathering are visible on the grains too (fig. 6E). Their share is higher in the samples LQ5 and LQ6 whereas the mostly fresh grains occur in the samples LQ2 to LQ4 and LQ6. Silica precipitation is visible on the grains from sites LQ2 and LQ3.

5 *Discussion*

5.1 *Chronology of local glaciations*

Exposure data and relative-age estimates obtained in the Łomnica and Łomniczka suggest that all preserved moraines in the study area originated during the last glaciation (Weichselian/Würmian) cycle. The measured SH data demonstrate that there is no significant difference in the degree of weathering between the sampled moraines in study area. This may be explained by rather old ages of tested surfaces concealing its weathering variations or by relatively narrow time span during which moraines were deposited and boulder surfaces exposed. Regarding the overall range of obtained SH data and only slightly higher R-value for the glacially abraded bedrock than for moraine boulders the second hypothesis seems to be more likely. This suggests that the moraines are only slightly older than the glacial surface at the foot of cirque headwall, implying the Late Quaternary age to all moraine systems.

Exposure ages which represent minimum age estimates for glacial surfaces in the Łomnica and Łomniczka valleys, allow for tentative reconstruction of the last glaciation history of the study area. Within the limits of available data, it appears that the lowermost preserved moraines (zone I) represent the initial advance of the Łomnica glacier during the last glacial period (OIS 2). Although exposure ages from these moraines are apparently lower than expected, the proximity and age of first recessional moraines (zone II) suggest that the lowermost moraines originated during the local maximum of the Last Glaciation (LGM). The set of recessional moraines in the zone II was deposited at around 17.0 ± 0.4 ka reflecting an oscillation of the glacier after the LGM. A Lateglacial re-advance of glacier occurred around 14.8 ± 0.5 ka leaving moraines at the lower limit of the cirque (zone III). The subsequent glacier retreat into the cirque was interrupted by a recession around 13.6 ± 0.9 ka when the last set of moraines was deposited near the cirque lake. The uncertainty of the single exposure age complicates the chronological correlation but does not preclude the Younger Dryas origin of moraines near the lake. The deglaciation terminated at the beginning of the Holocene when relics of the glacier melted at the foot of cirque headwalls (8.4 ± 0.3 ka) or in small hanging depressions.

Exposure-age estimates obtained from the lowermost moraines (zone I) are not consistent with the dataset indicating post-deposition changes of the lowermost moraines. Exposition of boulders can be modified due to frost-heave, thawing of dead ice, rotation or erosion. All these processes are spatially diversified affecting boulders on the moraine surface in various rate and yielding different exposure ages. However, dated boulders from the terminal moraine (Lo-6 and Lo-7) show a similar age. The vegetation cover cannot explain apparently younger exposure ages because it causes only changes up to 4 % in the production rate (Kubik et al. 1998). The effect of snow cover shielding can be more prominent (e. g. Benson et al. 2004, Favilli et al. 2009) but a small difference in altitude (300 m) and uniform topography within sampled localities restrict significant variations in the depth and duration of snow. The analysis of the grain size microtextures from Sites LQ5 to LQ7 suggests that the terminal moraine was reworked by gravitational mass-movement which transformed moraine morphology lowering moraine ridges into hummocky relief (fig. 7). The analysis show the effect of intensive crushing which erased the elements of abrasive action. Moreover, apparent precipitation and high proportion of broken grains suggest that this material was probably transformed after deposition by frost weathering. On the other hand the material sampled in the moraine zone II and III indicates strong influence of glacial abrasion on the grains. Angular and completely non-abraded grains dominate in the samples with only few traces of crushing in the sample from the moraine near the Mały Staw Lake. These observations indicate different genetic processes which affected material in the lowermost moraines (I) and higher moraine zones (II and III). The grains in the samples from lowermost moraine zone exhibit more complicated genesis of the deposits. Action of the glacial processes was followed by chemical weathering and subsequent frost shattering.

According to obtained ^{10}Be exposure ages, it can be suggested that the investigated moraine belts in the Łomnica and Łomniczka valleys reflect a single (Weichselian/Würmian) glaciation. This finding corresponds to relative-age estimates based

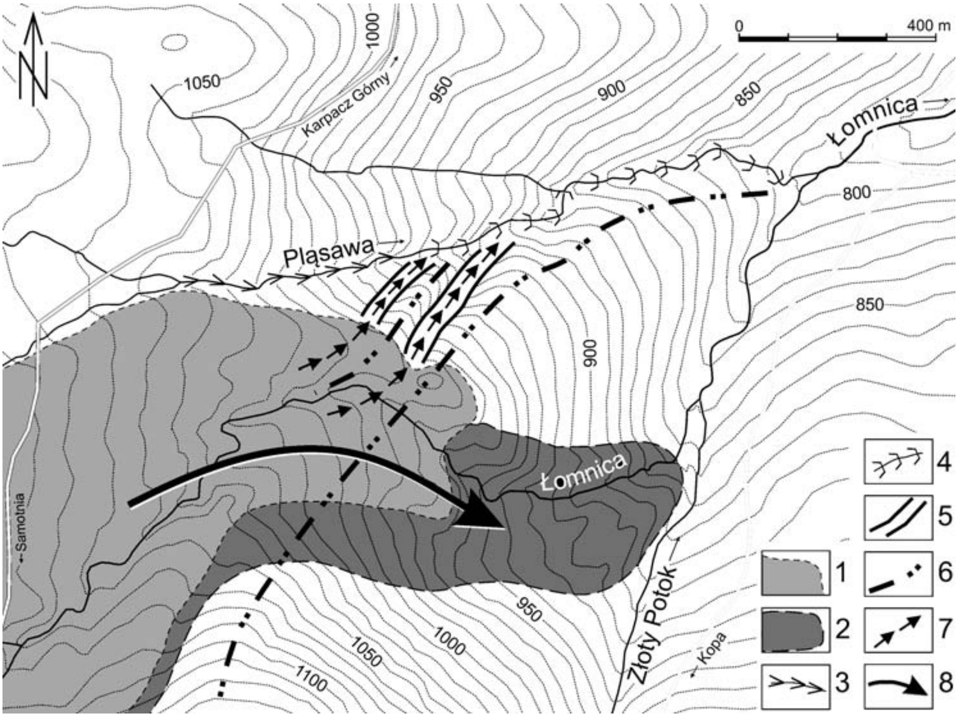

Fig. 7. Glacial transformation of the drainage network in the Łomnica Valley. 1 – younger glaciation (II), 2 – older glaciation (I), 3 – V-shaped channel, 4 – flat-bottomed channel; 5 – wind gaps; 6 – presumed pre-glacial watersheds, 7 – presumed pre-glacial courses of the Łomnica river; 8 – direction of the Łomnica glacial transfluence to the Złoty Potok Valley.

on SH measurements, implying a Late Quaternary origin to all preserved moraine systems within study area. The interpretation of numerical and relative-age chronological data appears to reject the idea of pre-Weichselian origin of moraines within the Łomnica valley suggested by TRACZYK (1989). These findings are echoed by BRAUCHER et al. (2006) and CARR et al. (2007) who find evidence only for Late Weichselian to early Holocene deglaciation from the nearby Úpa and Labe valleys. The exposure ages also correspond with the radiocarbon date reported by CHMAL & TRACZYK (1999) from the Łomnica cirque specifying a period of the glacier retreat and refining maximum age for presence of local glacier relics.

5.2 *Correlation of glaciations in the Łomnica and Úpa valleys*

As noted above, the timing of preserved moraines in the Krkonoše Mts has been traditionally attributed to either last glaciation or more glaciations. However, recent research and the data presented in this paper reject the second idea assigning only erosion landforms and relics of deposits to earlier glaciations. Obtained exposure ages and SH R-values along with published numerical age estimates and relative-age data (BRAUCHER et al. 2006, CARR et al. 2007) enable tentative correlation of the local Quaternary glaciations chronologies across the mountain range.

The SH data measured on moraines in the Łomnica and Łomniczka valleys are apparently higher then R-values referred by CARR et al. (2007) from the upper Úpa valley. The difference results from various types of granites which build bedrock in the source areas of moraine boulders. Regarding this fact the obtained SH data cannot be used neither for dating of moraines (sensu ENGEL 2007) nor for direct correlation of moraines in the Łomnica, Łomniczka and Úpa valleys. However, it is evident from ranges of mean R-values that all the preserved moraine ridges in these valleys have originated during the Late Quaternary probably. Exposure ages from three moraine zones suggest that three major periods of glaciation may be recognized in the Łomnica valley. The most extensive of these glaciations appears to have originated during the LGM or during earlier stages of the last glaciation. A major readvance of the glacier occurred around 17 ka when recessional moraines terminated not far from the limit of the previous glaciation. The last period of glaciation correlates with the Lateglacial period during which moraines located higher in the Łomnica cirque were deposited.

^{10}Be dating reported by BRAUCHER et al. (2006) from the Úpa valley provides information for roches moutonnées that originated during the deglaciation period of the last glaciation (fig. 8). A combination of exposure ages and R-values for the dated surfaces allow to obtain age estimates for the SH measurements (ENGEL 2007). Application of the SH dating technique on preserved moraine systems in the Úpa valley implies a Late Weichselian age (CARR et al. 2007). Relics of glacial sediments described from the lower part of the Úpa valley (Pec pod Sněžkou) was associated with the Weichselian glaciation following the river terrace sequences (CARR et al. 2002). Tentative interpretations on the basis of exposure ages, R-values and sedimentary evidence suggest that the terminal moraine (I) in the Łomnica valley may be associated with the last glaciation (OIS 2 or 4) and possibly relates to the glacial deposits in Pec pod Sněžkou. The remaining moraines (II to III) in the Łomnica valley record progressive glacier retreat subsequent to the regional LGM and probably correlate with the preserved moraine ridges located in the upper Úpa valley.

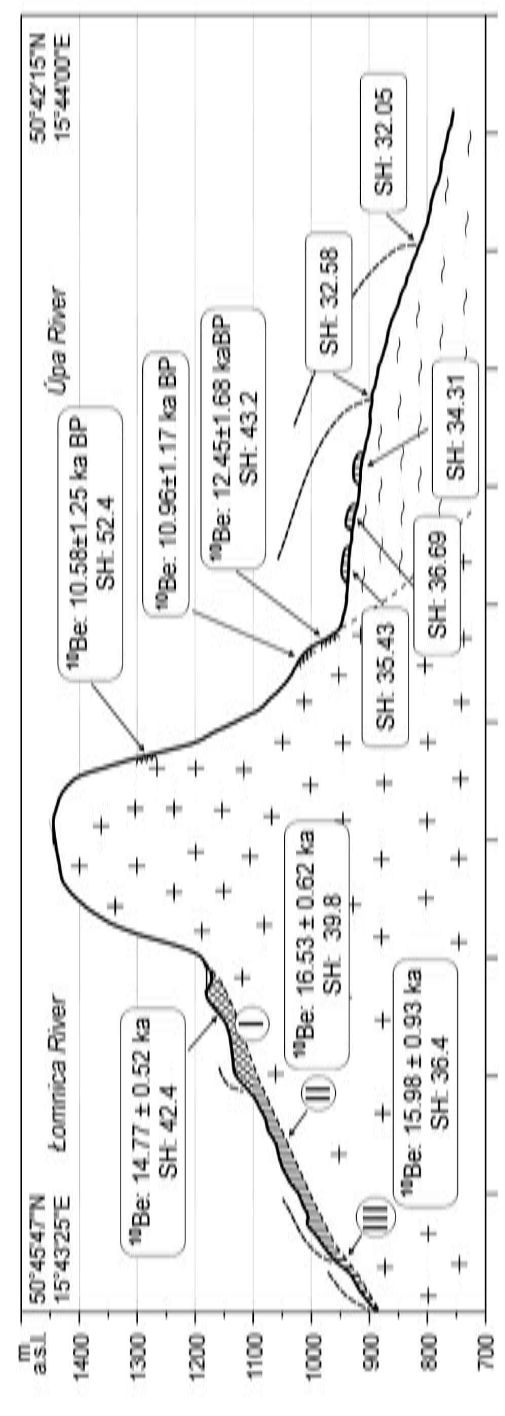

Fig. 8. Summary profile for ^{10}Be dating and Schmidt-hammer measurements in the Łomnica and Úpa valleys. I–III – moraine zones.

5.3 *Implications for the Hercynian ranges in Central Europe*

The Krkonoše Mts belong to the few Hercynian mountain areas in Central Europe which were glaciated during the Quaternary. Within a periglacial environment between the Scandinavian ice sheets and the glaciated area of the Alps, isolated mountain glaciations developed in the Vosges, the Schwarzwald, the Harz, the Šumava/ Bayerischer Wald and the Hrubý Jeseník as well. Local glaciations of these mountains may provide important palaeoclimatic information for large regions of Central Europe, as mountain glaciers are a very sensitive indicator of climatic oscillations (e. g. Menzies 1996). Moreover, this information is highly significant for establishing local stratigraphy, since mountain environments generally lack sufficient sedimentary record. However, due to scarce glacial deposits and limited extent of glacial landscape, glaciation chronologies for the noted mountain areas are poorly understood (e. g. Traczyk 1989, Rother 1995). In this respect, the Krkonoše Mts together with the Vosges and the Šumava/Bayerischer Wald are the most important areas with a well-preserved record of glaciation.

Up to the present time a consistent chronological data for local Quaternary glaciations was derived only from the Vosges and the Bayerischer Wald. Both the Hercynian ranges were repeatedly glaciated throughout the Quaternary (e. g. Woillard 1979, Hauner 1980). Glacial chronology from the western part of the Vosges suggests a maximum glacial advance preceding the last interglacial whereas moraines from the eastern flank are referred as Late Würmian (Seret et al. 1990, Mercier & Jeser 2004). Radiocarbon dating and palynological studies from the Vosges indicate cold climate between 25 ka and 15 ka BP and subsequent glacial retreat (Woillard 1979, Flageollet 2002). ^{10}Be exposure ages of moraines and bedrock in five valleys in the eastern part of the Vosges were associated with deglaciation phase of the last glaciation around 10.2 ± 0.45 ka (Braucher et al. 2006).

A few chronological studies describe the timing of the Quaternary glacial advances in the Bayerischer Wald. Exposure age of 61.5 ± 3.1 ka from bedrock surface in the Grosser Arber summit region was interpreted as a result of a more extensive glaciation during the early Würmian (Reuther 2007). The most recent period of glaciation was restricted to 12,470 ± 202 ^{14}C years BP and 32.4 ± 9.4 ka BP in the Kleiner Arbersee area using radiocarbon and IRSL methods respectively (Raab 1999, Raab & Völkel 2003). A detailed chronology of Late Würmian advances of the Kleiner Arbersee glacier as well as minimum age of previous glaciation was determined using ^{10}Be exposure dating (Reuther 2007). ^{10}Be exposure ages show that the maximum glacial advance in the Late Weichselian occurred before 20.7 ± 2.0 ka. During the last readvance (15.5 ± 1.7 ka) the glacier deposited moraine damming the Klein Arbersee Lake and had melted back by 14.5 ± 1.8 ka. Radiocarbon age of ~ 14 ka cal. BP from cirques in the Plechý and Poledník mountains were interpreted as the termination of the last glaciation on the Czech side of the mountains (Pražáková et al. 2006, Mentlík et al. 2010).

All preserved moraine ridges in the Łomnica and Łomniczka valleys represent the last (Weichselian) glaciation, similarly as dated moraines in the Bayerischer Wald and moraines at the eastern side of Vosges. Although any numerical data have been obtained on moraines for earlier substage of the last glaciation, geomorphological and sedimentary evidence together with exposure ages of bedrock confirm the presence of pre-Late Weichselian glaciers in these areas. The Krkonoše Mts ^{10}Be chronology indicates that a Late Weichselian glacier advance was preceded by a more extensive earlier advance which confirms the interpretation of exposure dating presented by Reuther (2007) for the summit area of the Grosser Arber. Within the limits of available exposure data, it appears that the deglaciation period in the Krkonoše Mts coincides with periods of glacier retreat both in the Bayerischer Wald and in the eastern part of the Vosges.

6 *Conclusions*

Exposure ages and Schmidt hammer data obtained in the Łomnica and Łomniczka valleys indicate younger ages of moraines than previously considered. Similar ^{10}Be ages and R-values measured on glacially abraded bedrock in the cirque and on moraines suggest that all preserved moraines originated during the last glaciation (Weischselian/Würmian) cycle. The range of numerical data further indicates relatively short duration of the glaciation lasting from the LGM to the Lateglacial period. It appears that the deposition of moraines before 17.0 ± 0.4 ka and terminated around 13.6 ± 0.9 ka. Exposure age for the foot of cirque headwall (8.4 ± 0.3 ka) suggests that glacier persisted in favourable sites until the beginning of the Holocene. These findings have critical implications for the traditional model of glaciation in the Krkonoše Mts. Key questions for future investigations are: Is it possible that cirques originated during the last glaciation only? If the area was glaciated earlier why moraines do not stand out in the landscape?

Analyses of quartz grain microforms in samples from the terminal moraines indicate effects of chemical weathering and frost shattering which have obscured original elements of glacial action. Frequent precipitation and high proportion of broken grains suggest that the surface of the lowermost moraine zone was transformed by post-deposition changes. Thus, exposure ages from the lowermost zone refer to termination of the post-depositional moraine surface transformation rather than to deposition period.

It is suggested that further investigations and dating are necessary to validate the proposed glaciation chronology and to reliably correlate moraines within the Krkonoše Mts as well as with records of glaciations from Hercynian mountains in Central Europe.

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